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A Study on Pulsed Power Supply based on Separate Excitation

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Abstract:

Regular power supply cannot be used for some special applications such as discharging plasma generator, air purification system, medical discharging equipment, etc. Instead, a special low-power high-voltage pulsed power supply is required. In this paper, the design and simulation of a separate excited pulse power supply are proposed. The power supply can produce high-voltage small-current pulses adaptive to different loads. The working principle of the power supply is analyzed. A comparison between this power supply and other pulsed power supply based on capacitance energy storage is discussed. The circuit implementation of power supply is proposed. The key component for the power supply, pulse transformer, as well as other components is studied in detail. Based on the analysis, an optimized design of the power supply is proposed. Computer simulation is used to verify the performance of the designed power supply, such as the output characteristics under different load resistances, the pulse frequency and the duty ratio. Simulation results demonstrate the effectiveness of the designed power supply. Some possible performance improvements on the power supply are also suggested. The designed power supply can satisfy the requirements for commercial applications such as plasma generation and air purification system.

Keywords: Pulsed power supply, high voltage pulse, separate excitation, pulse transformer

1. Introduction

Power supply has become one of the most important parts in many electrical or electronic equipments used in both academic and industrial fields. Such applications require power supplies with high efficiency, good quality and high stability. Furthermore, for some special applications such as discharging plasma generator, air purification system, and medical discharging equipment, the regular power supply cannot be used. Instead, a special low-power high-voltage pulsed power supply is required [1]. In it, a very high voltage is needed for plasma excitation. Further, the pulse needs to be very narrow so that the electrons can be accelerated to gain enough energy to escape from the control of nuclei for plasma generation [2].

During the past twenty years, many progresses have been made in power electronics. High power semiconductor devices such as GTO (Gate-Turn-Off Thyristor), GTR (Giant Transistor), MOSFET (Metal Oxide Semiconductor Field Effect Transistor), and IGBT (Insulated-Gate Bipolar Transistor) have been developed [3]. Based on them, a separately excited pulse power supply is designed in this paper to meet the requirements of plasma generator [4]. It is called separately excited power supply because the pulse is generated by a semiconductor instead of RLC circuit.

This paper is organized as below. First, we will briefly review the recent works by others in pulsed power techniques in section 2. The circuit design of the separately excited pulse power supply and its components is shown in section 3. In section 4 we will analyze the key components of the power supply, the pulse transformer and the control parts in detail. Next, the simulation results of the designed power supply are shown in section 5 to demonstrate its effectiveness. Finally, section 6 concludes the work and suggests some future work to further improve the power supply design.

2. Previous Work on Pulsed Power Supply

There are two major categories of pulsed power supplies which are in use now. The first category generates the pulse with high power switch and delivers it to the load through the pulse transformer directly. The second category first produces the high voltage by semiconductor switch and transformer, then uses the high power high frequency switch to generate the pulse. For the first category of pulsed power supplies, it is challenging to make the high power pulse transformer. It is also costly, and may have some hysteresis effects [5]. Based on above considerations, we are using the second instead of the first category for our pulsed power supply design. There are many possible designs for the power supply in the second category. The basic design we used in our pulsed power supply is shown in Fig. 1.

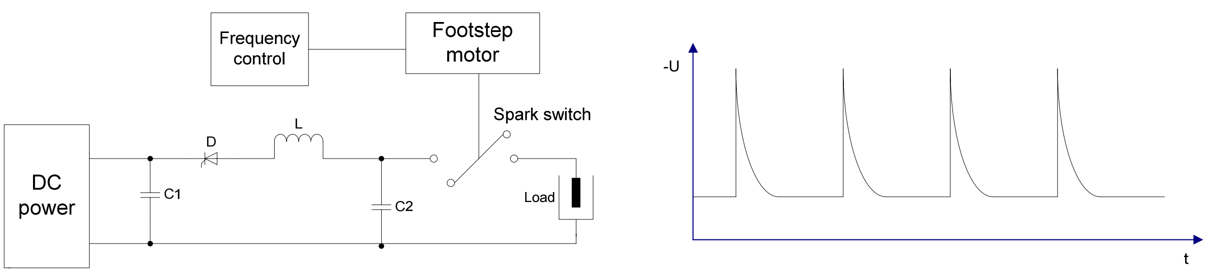


Figure 1. The circuit structure and output pulse of the pulsed power using DC power as source

The above power supply design can produce low power, high voltage, narrow pulsed power which satisfies the requirements for plasma generator. It has the advantage that the source power can be DC or any other kinds of power supply. In this way, it can be used for various applications. Further, the spark switch is controlled by footstep motor. Thus the frequency of the pulse can be easily controlled by the footstep motor. Some further improvements on the above design are still possible. For example, if the DC power can be replaced with AC power, the application of such power supply may be further broadened and it can produce high voltage convenient for further processing. The capacitance may also be deleted so that the spark switch can be connected to the source power supply directly. In this way, it can produce high voltage pulse from the source power and we can focus our design on this part only [6].

There are mainly two methods to produce high voltage pulse power. The first method is to produce high voltage directly using pulse transformer. The second method is to produce high voltage using DC chopper. The first method is easy in implementation due to its simple structure. However, its parameters can be modified only in a small range. Further, the design of the transformer is costly and takes long time. However, such limitations can be avoided in the second method. In the second method, the parameters (such as frequency, duty ratio) can be modified in a large range. It can produce very fine and complex high voltage pulsed power. Although the structure of the second method is also complex, but it is not too difficult to design and make it.

Based on above considerations, the second method is used for the pulsed power supply design. In order for it, a proper switch which can produce such high frequency and high voltage pulse should be selected. The semiconductor switch is a good choice for the pulse generator in the transformer design. IGBT has a switch speed of 0.1~1.0ns and working frequency from thousands to tens of thousands hertz. It can also work under 400A/2000V environment. Thus, it is a suitable choice for the transformer design. The spark switch can endure higher voltage and higher frequency than IGBT. It is good to be used as the switch to generate the pulse of the output. [7]

3. The Structure and Components of the Pulsed Power

Based on the above analysis, a separate excitation pulsed power supply is designed in our work. It is called "separate excitation" because the frequency and duty ratio of the input pulse are modified before the pulse is input to the transformer. The working principle of this design can be explained as follow. The AC power is transformed to high voltage by pulse transformer and then rectified by voltage rectifier. Finally, the high voltage, high frequency pulse is generated by spark switch and output to the load. The main circuit of the design is shown in Fig. 2.

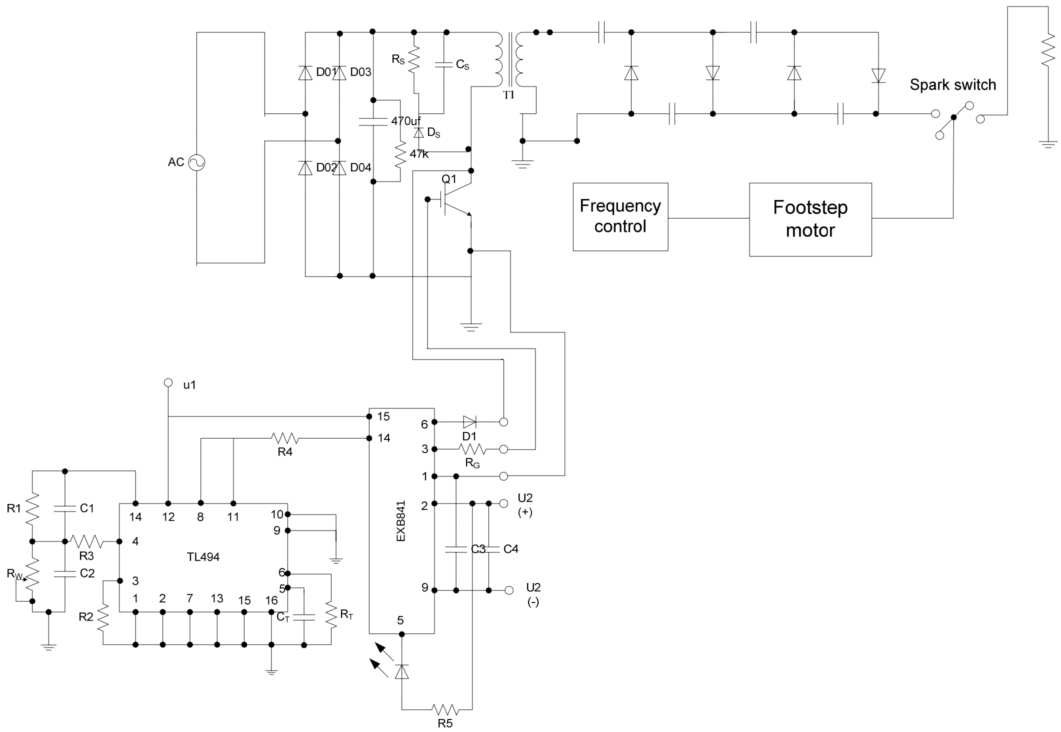


Figure 2. The circuit of the pulsed power supply

According to Fig. 2, the AC source power is rectified and filtered by D01~D04 and C0. It becomes a DC power which is input to the pulse transformer and IGBT (the semiconductor switch). The IGBT switch works under the control of PWM (Pulse Width Modulation) pulse signal generated by the controlling circuit. The high voltage, high frequency pulse can be produced by the pulse transformer on the second side. The power is then rectified by the four-time rectifier and becomes high voltage DC power. The voltage of the DC power can be modified by changing the duty ratio made by the controlling circuit. The high voltage, high frequency and narrow pulse is generated by spark switch. The widths of the pulse are determined by the turn-on and turn-out time of the switch. The frequency of the pulse is determined by the frequency control circuit of the footstep motor.

4. The Pulse Transformer and the Controlling Circuit

Pulse transformer can transform the pulse power and its design cannot be too large [8]. The ratio between the numbers of loops in the second side (N_2) and the number of loops in the first side (N_1) also cannot be too large in order to reduce the energy loss due to capacitance between the loops [9]. The current in the capacitance can be calculated from equation (4.1), as shown below. In it, I_s is the charge current of the capacitance, U_1 is the voltage of the second side of the transformer, C_s is the capacitance between the loops, and f is the frequency of the power. [10]

$$I_s=4U_1C_s(N_2/N_1)^2f \tag{4.1}$$

We can see that due to the capacitance C_s, the current in high frequency will be very large. This can lead to a large energy loss in the transformer, which will degrade the energy efficiency of the pulsed power supply. The capacitance between the loops and the layers is shown in Fig. 3. The structure of the transformer loop is also shown in it [11].

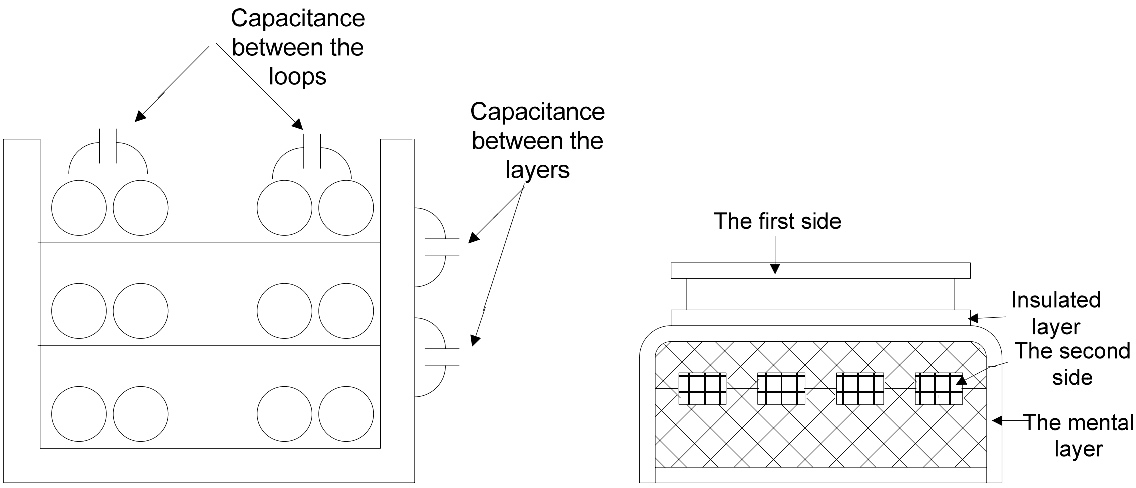


Figure 3. The capacitance between the loops and layers and the structure of the transformer's loop

In order to reduce the energy loss in the transformer, we can separate the loop so that the capacitance between the loops and the layers can be reduced [12]. Furthermore, the shape of the core design is also very important. Fig. 4 shows the optimized transformer design in order to reduce the capacitance hence the energy dissipation due to it [13].

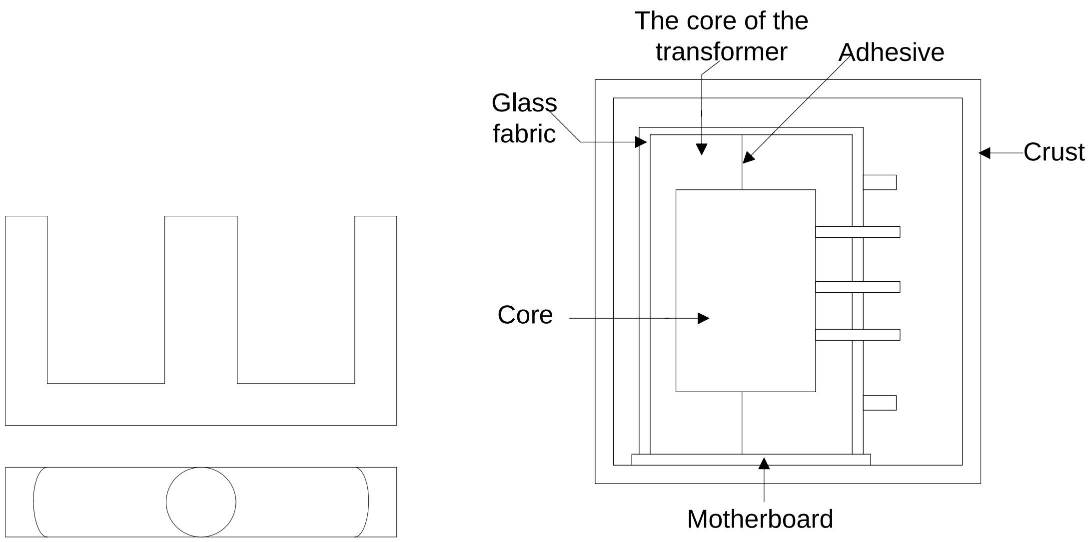


Figure 4. The optimized design for the core of transformer and the structure of the transformer

The structure design of the transformer is also shown in Fig. 4. Such core design not only reduce the energy lose but also make the size of the whole transformer smaller [14].

The controlling circuit is the PWM circuit. In this work, the TL494 and EXB841 are used to control the frequency and duty ratio of the produced by IGBT. The diagram of the controlling circuit is shown in Fig. 5.

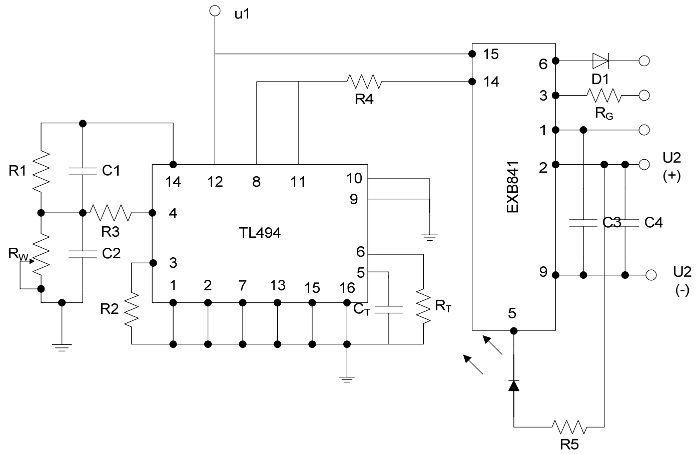


Figure 5.The circuit of the controlling system

As shown in Fig. 5, R_1, C_1, R_w construct a circuit which can prevent the concussion to the whole power supply when it turns on. R_1 and R_w can also help prevent the saturation of the core of the transformer. R_w is a resistor whose resistance value can be adjusted. By adjusting the value of R_w, the duty ratio of the pulse can be modified. The frequency of the pulse can be easily controlled by R_T and C_T, as shown in Equation (4.2).

$$f_{osc} = \frac{1.1}{R_T \cdot C_T} \tag{4.2}$$

5. Simulation Results and Discussion

The pulsed power is simulated with Multisim software to verify its function. After we decided the values of the components in the system, we simulated the design under different frequencies, duty ratios and loads. The collected data are plotted in a curve to analyze the performance of the designed pulse power supply under different situations. The circuit used for simulation is shown in Fig. 6.

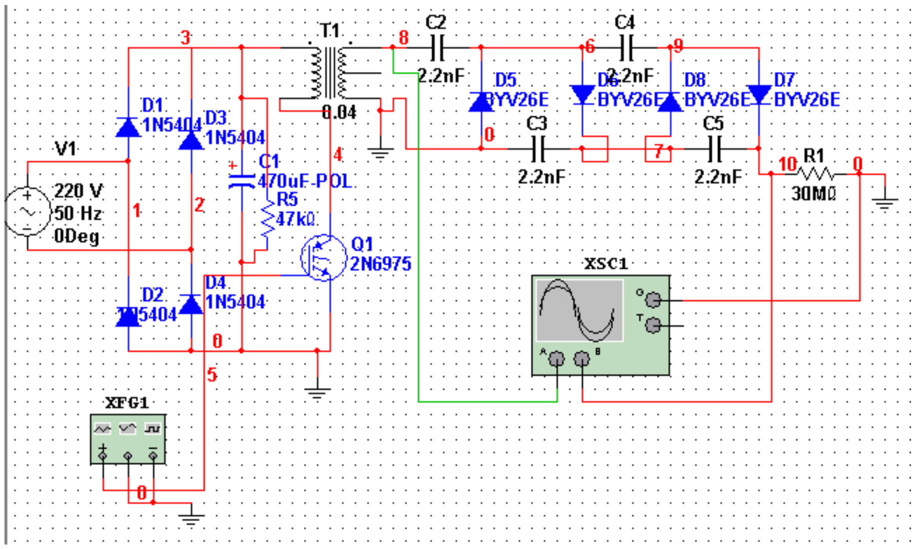
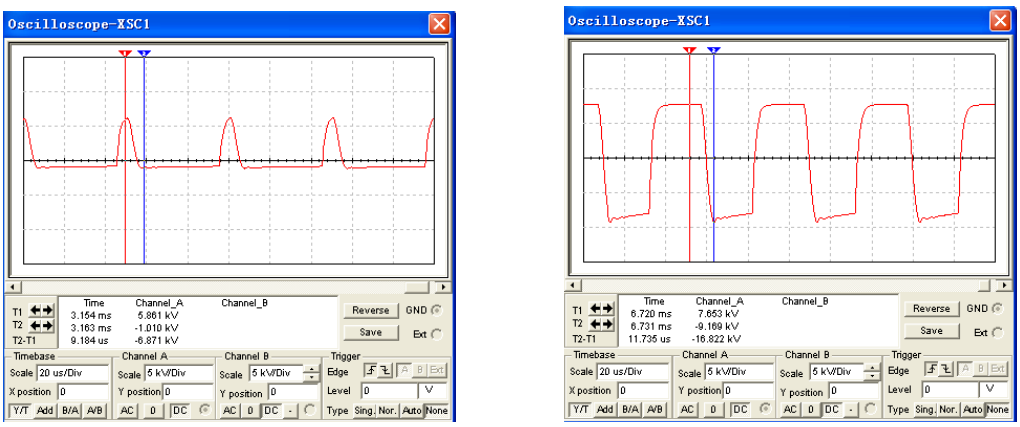


Figure 6. The circuit diagram for the simulation

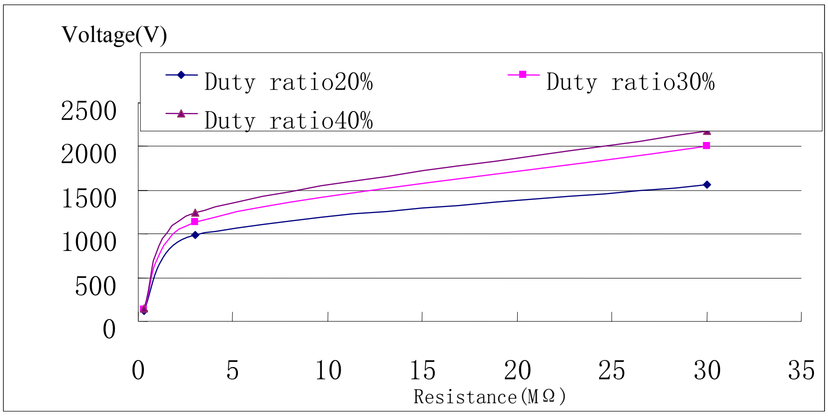
As shown in Fig. 6, if we change the frequency or the duty ratio of the PWM system by XFG1, or if we change the load of the system, the output change can be observed on the oscillograph XSC1. The pulse we get from the transformer is shown in Fig. 7 [15].



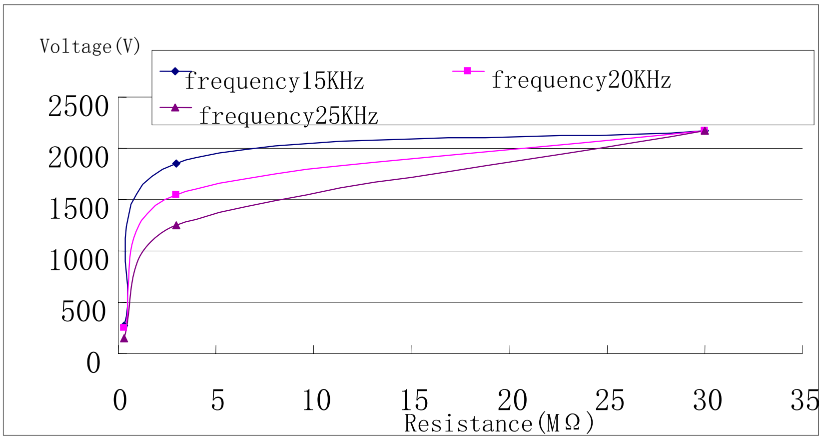
(a) The duty ratio is 10% (b) The duty ratio is 50%

Figure 7. The output pulse get from the second side of the transformer

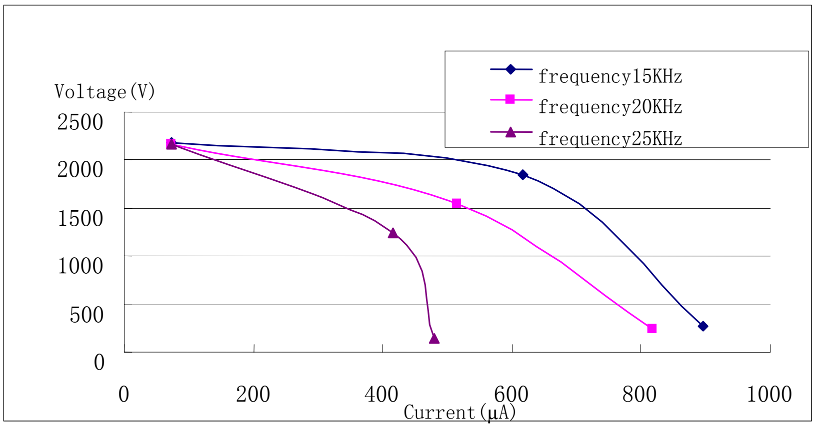
From Fig. 7 we can see that if we only change the duty ratio but fix the frequency and load, the width of the pulse becomes wider and its value is increased [16]. The shape of the output pulse, the voltage value, as well as the pulse width and the duty ratio change with the duty ratio, frequency and the load. The relationship between the output voltage and different input conditions is shown in Fig. 8 [17].



(a) The output voltage v.s. load resistance under different duty ratios (frequency:25KHz)



(b) The voltage v.s. load resistance under different frequencies (duty ratio: 40%)



(c) The Volt-Ampere characteristics of the power under different frequencies (duty ratio: 40%)

Figure 8. The output characteristics of the power under different conditions

As shown in Fig. 8(a), the output pulse voltage increases as the load resistance increases in 0~30MΩ range. Under the same load resistance, the larger the duty ratio is, the larger the voltage is. Fig. 8(b) shows that the output pulse voltage increases as the load resistance increases in 0~30MΩ range. Under the same load resistance, the smaller the frequency is, the larger the output pulse voltage is. However, if the load resistance is too large (beyond 30MΩ), this rule is no longer valid and the output voltage will become the same for different frequencies. In this way, the frequency affects the characteristics of the power supply only for small load resistance. If the load resistance is too large (beyond 30MΩ), the power supply will be no longer affected by the frequency. Fig. 8(c) shows that for frequency under 15KHz, the output voltage doesn't drop too quickly as the current increases. This is actually a very good characteristic for the power. Thus, it is a suitable frequency of 15 KHz for the semiconductor switch (IGBT) to generate the pulse to the transformer.

6. Conclusion

In this paper, we proposed the design and simulation of a pulsed power supply based on separate excitation. The proposed pulsed power supply can be used for applications such as discharging plasma generator, air purification system, medical discharging equipment, etc. The design and analysis of each component in the pulsed power supply is discussed. Multisim simulation is used to verify the correct function of the power supply. Simulation results indicate that the frequency, duty ratio and load resistance have close relationship with the output pulse voltage value. The power supply can only work with some certain frequency range, and the effect of the frequency decreases as the load resistance increases. Modifying the duty ratio is an effective way to change the output pulse voltage value. However, due to the saturation effect of the core, the duty ratio should not go beyond 50%. Changing the load resistance can be an effective way to adjust the output pulse voltage value. In the future work, we plan to further improve the pulsed power supply design so that it can work with various kinds of loads. Furthermore, we will increase the maximum load resistance it can drive, so that it can be used for more applications.

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